

B meson mixing at CDF II

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We present the first limit on B_s^0 mixing frequency obtained using 360 pb⁻¹ of Tevatron Run II data with the CDF II detector. We derive $\Delta m_s > 7.9$ ps⁻¹ @ 95% C.L. with a sensitivity of 8.4ps⁻¹.

1. Introduction

In the Standard Model (SM) flavor mixing of neutral mesons is induced by second-order charged weak interactions through box diagrams. For B_d^0 the mixing frequency, Δm_d , is $\propto f_{B_d}^2 B_{B_d} |V_{td}|^2$ and thus provides a constraint on the usual unitarity triangle whereas for B_s^0 $\Delta m_s \propto f_{B_s}^2 B_{B_s} |V_{ts}|^2$ and is much higher since $|V_{ts}| \gg |V_{td}|$. Theoretical uncertainty on the hadronic parameters make the constraint from the precise Δm_d measurement weak. On the other end a measurement of the mixing frequency ratio $\Delta m_s / \Delta m_d$ would fix the ratio of hadronic parameters thus allowing a much tighter constraint on the unitarity triangle. The expected range for Δm_s from the analysis of all available B and Kaon physics data within the SM is getting narrower and narrower ($\Delta m_s \in [15.6, 23.1]$ @ 95% C.L. [1]). Observing B_s^0 mixing outside the SM favored range would be a signal for new physics. Experiments at LEP and SLD as well CDF in Run I have only provided a lower limit $\Delta m_s > 14.5$ @ 95% C.L. [2]. The high frequency expected for B_s^0 flavor oscillations poses formidable experimental challenges related to the need for extremely accurate proper time resolution in order to resolve the oscillation pattern. This is clearly reflected in the approximate expression for the significance of the mixing amplitude measurement [3]

$$S = \frac{A}{\sigma_A} \simeq \frac{S}{\sqrt{S+B}} \sqrt{\frac{\varepsilon D^2}{2}} e^{-\frac{1}{2}(\sigma_{c\tau} \Delta m_s)^2} \quad (1)$$

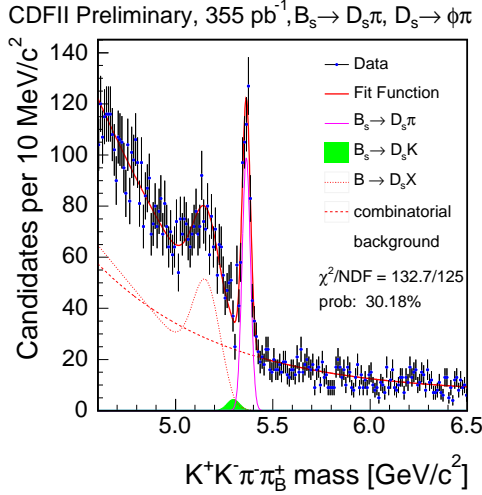
where S is the signal sample size, B is the background, ε is the efficiency for flavor tagging and D

is the tagging dilution defined as $\frac{N_R - N_W}{N_R + N_W} = 1 - 2w$, where the mistag rate $w = N_W / (N_R + N_W)$ is the fraction of B candidates with an incorrectly assigned flavor. The effect of finite resolution on proper time ($\sigma_{c\tau}$) reduces the statistical significance of the measurement, especially at high values of Δm_s . A key point of the CDF upgrade for Run II has been the capability of triggering on hadronic decays of B mesons allowing the collection of fully reconstructed B_s^0 decays. Despite the limited statistics available in these modes the excellent proper time resolution significantly helps the current sensitivity of CDF and will offer the unique chance of a determination of Δm_s from CDF data alone. We describe here the first search for B_s^0 mixing using 360 pb⁻¹ of Run II data.

2. CDF II Detector and Trigger

The upgraded CDF detector for Run II [4] has been designed to enhance the sensitivity to B_s^0 mixing, in particular with the L00 [5] layer of silicon detector very close to the beam pipe, the TOF system [6] and the Silicon Vertex Tracker (SVT) [7]. This latter device, reconstructing on-line tracks in the silicon tracker, enabled triggering on B -decay vertices, for the first time at a hadron collider. The current CDF b -physics related trigger menu is based on the following selections:

- Di-muons with muon transverse momenta $P_T > 1.5$ GeV/ c to select $b \rightarrow J/\psi X$ decays.
- Single muon or electron with $P_T > 4$ associated with a displaced trigger track with

Figure 1. $\bar{B}_s^0 \rightarrow D_s^+ \pi^-$, $D_s^+ \rightarrow \phi \pi^+$ signal.

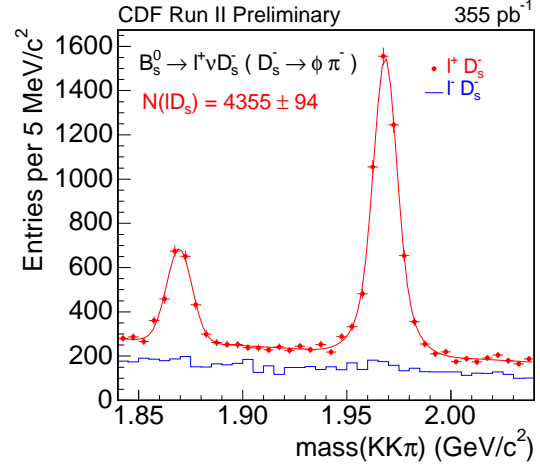
impact parameter greater than $120 \mu\text{m}$ (lepton+SVT).

- A Two Track Trigger (TTT) requiring two displaced SVT tracks with impact parameters greater than $120 \mu\text{m}$, consistent with originating at a vertex $200 \mu\text{m}$ away from the beam axis.

These different triggers provide large samples of, respectively, $B_{d,u} \rightarrow J/\psi K^{(*)}$, $B_{d,u} \rightarrow l D^{(*)} X$ and $B_{d,u} \rightarrow D^{(*)} \pi$ used to calibrate the vertex resolution function, the flavor-tagging dilution and to extract the impact parameter trigger bias. These measurements are an essential part of the B_s mixing study making the latter really the “ultimate” b -physics analysis at CDF.

3. Signal samples

Currently we reconstruct $\bar{B}_s^0 \rightarrow D_s^+ \pi^-$ (hadronic analysis) and $\bar{B}_s^0 \rightarrow D_s^+ l^- X$ channels (semileptonic analysis). In both cases the $D_s^+ \rightarrow \phi \pi^+$, $D_s^+ \rightarrow \bar{K}^{*0} K^+$ and $D_s^+ \rightarrow \pi^+ \pi^- \pi^+$ decay modes are used, where the light meson resonances are detected in the $\phi \rightarrow K^+ K^-$ and $K^{*0} \rightarrow K^+ \pi^-$ channels only. These modes combined correspond to 4.9% of the total D_s decay rate.

Figure 2. $\bar{B}_s^0 \rightarrow D_s^+ l^- X$, $D_s^+ \rightarrow \phi \pi^+$ signal.

B_s^0 meson signals are identified as sharp peaks either in the reconstructed B_s^0 mass for hadronic decays or in the D_s mass for opposite sign combinations of a lepton (μ or e) and a D_s^\pm meson candidate.

B meson candidates are reconstructed starting from charged tracks and leptons matched to trigger objects satisfying on-line trigger selections, in order to accurately model trigger biases to the signal proper time distribution through Monte Carlo (MC) simulations. To ensure optimal vertexing and momentum resolution only tracks reconstructed both in the central drift chamber and in the silicon vertex detector with a minimum transverse momentum of $400 \text{ MeV}/c$ are used. A secondary/tertiary vertex fit is performed on all possible track combinations using a mass constraint on D_s mesons involved in hadronic decays. Further selection criteria have been designed to optimize $S/\sqrt{(S+B)}$, using MC simulations for signal and sideband data for background.

Hadronic decays are selected requiring a significantly displaced secondary vertex and a tertiary vertex consistent with a downstream decay of a charmed meson. Selecting high probability vertex fit reduces combinatorial background and a minimum P_T on the pion from B_s^0 decay is required to reduce background from D_s production

Table 1
 B_s^0 yield and S/B in 360 pb $^{-1}$ of CDF II data.

| Decay Channel | Yield | S/B |
|--|---------------|-----|
| $\bar{B}_s^0 \rightarrow D_s^+ \pi^-, (\phi \pi^+)$ | 526 ± 33 | 1.8 |
| $\bar{B}_s^0 \rightarrow D_s^+ \pi^-, (\bar{K}^{*0} K^+)$ | 254 ± 21 | 1.7 |
| $\bar{B}_s^0 \rightarrow D_s^+ \pi^-, (\pi^+ \pi^- \pi^+)$ | 116 ± 18 | 1.0 |
| $\bar{B}_s^0 \rightarrow D_s^+ l^- X, (\phi \pi^+)$ | 4355 ± 94 | 3.1 |
| $\bar{B}_s^0 \rightarrow D_s^+ l^- X, (\bar{K}^{*0} K^+)$ | 1750 ± 83 | 0.4 |
| $\bar{B}_s^0 \rightarrow D_s^+ l^- X, (\pi^+ \pi^- \pi^+)$ | 1573 ± 88 | 0.3 |

in $p\bar{p} \rightarrow cX$ events combined with a fragmentation track. Remaining background sources are combinatorics and partially reconstructed B decays. The former is modeled by exponential functions and fixed by fits to the high mass B_s^0 sideband while the latter appear as a well separated bump to the low mass side of the signal peak. From MC simulation we derive shapes for the contributions from decays like $B_s^0 \rightarrow D_s^* \pi \rightarrow D_s(\gamma, \pi^0) \pi^+$ or $B_s^0 \rightarrow D_s \rho^+ \rightarrow D_s \pi^+(\pi^0)$ where the γ or π^0 escape undetected. Other backgrounds considered are Cabibbo-suppressed $B_s^0 \rightarrow D_s K$ decays (whose contribution is fixed to the analogous B_d^0 decay rate) and reflections from b-baryon and B_d^0 decays whose shapes and relative contributions are fixed to those expected from simulation.

Similar selection criteria are used to isolate semileptonic decays. Further requests on the K^* and ϕ helicity angle and on the the lepton + D_s invariant mass ($2.3 < m_{lD_s} < 5$ GeV/ c^2) reduce combinatorial and $c\bar{c}$ background. An important background (of order 20% of the signal sample) arises from $B \rightarrow D_s^{(*)} D_{(s)}^{(*)} X$ with $D_{(s)}^{(*)} \rightarrow l\nu X$ decays. The expected contribution is determined from MC using world average branching ratios and considered in the mixing analysis with proper lifetime and mixing probabilities. The background from real prompt $D_s^{(*)}$ paired with a random track faking a lepton (prompt background) is estimated from wrong sign, $l^\pm D_s^\pm$, signal. Its contribution is about 4% of the right sign sample.

An example of the clean signals observed in hadronic and semileptonic decays is shown in Figs. 1 and 2. Number of events and S/B val-

ues extracted from fits to the B_s^0 or D_s invariant mass are displayed in Table 1.

4. Proper Time Reconstruction and Resolution

The proper decay time of B_s^0 mesons is reconstructed using the distance in the transverse plane from the beam axis to the decay vertex (L_{xy}) and the transverse momentum of the candidates: $c\tau_{B_s} = L_{xy} \cdot m_{B_s} / P_T$. For semileptonic decays a K factor is needed to compensate for missing momentum carried by neutrinos $c\tau_{B_s} = K \cdot c\tau_{B_s}^*$ where $c\tau_{B_s}^*$ is reconstructed from the lepton + D_s transverse momentum. The K factor distribution is derived from MC simulation of inclusive semileptonic decays.

The time dependent mixing probability is convoluted with a Gaussian resolution function using the event-by-event expected error on $c\tau_{B_s}$. The latter includes a scale factor derived studying the proper time resolution function on a sample of pseudo- B_s^0 candidates constructed from a prompt D_s meson paired with a fragmentation track. This sample exhibits characteristics very similar to those of the signal and allows the parameterization of the scale factor as a function of several kinematic variables. The average $c\tau$ uncertainty for the golden $\bar{B}_s^0 \rightarrow D_s^+ \pi^-, D_s^+ \rightarrow \phi \pi^+$ mode is ≈ 100 fs corresponding to 60-70 μm resolution on the B_s^0 decay length. Note that the exponential term in eq. 1 implies a 60% loss of statistical power for 100 fs resolution at $\Delta m_s = 15$. Improving the proper time measurement accuracy, e.g. by using an event-by-event primary vertex, will certainly help in a future updated analysis.

5. Lifetime Measurement

Determinations of B -meson lifetimes in several exclusive B^+ and B_d^0 decay channels provide an important check on the accuracy of proper time measurement. This has been successfully performed [8] using $B \rightarrow J/\psi K^{(*)}$ and semileptonic decays collected with a version of the trigger with no impact parameter requirement on tracks. For the present mixing analysis an ad-

Table 2

Tagging dilution, efficiency and calibrated εD^2 (%) with statistical and systematic uncertainty.

| Tagger | $\sqrt{\langle D^2 \rangle}$ | ε | $\varepsilon(DS_D)^2(semil.)$ | $\varepsilon(DS_D)^2(had.)$ |
|--------|------------------------------|---------------|-------------------------------|-----------------------------|
| SMT | 35.9 | 5.0 | $0.557 \pm 0.047 \pm 0.034$ | $0.46 \pm 0.11 \pm 0.03$ |
| SET | 29.4 | 3.5 | $0.293 \pm 0.033 \pm 0.017$ | $0.18 \pm 0.06 \pm 0.02$ |
| JVX | 16.9 | 9.8 | $0.263 \pm 0.035 \pm 0.021$ | $0.14 \pm 0.07 \pm 0.01$ |
| JJP | 11.5 | 14.0 | $0.150 \pm 0.026 \pm 0.015$ | $0.11 \pm 0.06 \pm 0.01$ |
| JPT | 5.0 | 52.0 | $0.157 \pm 0.027 \pm 0.025$ | $0.24 \pm 0.09 \pm 0.01$ |
| Total | 35.9 | 5.0 | 1.429 ± 0.093 | $1.12 \pm 0.18 \pm 0.04$ |

ditional crucial point has been the removal of the bias introduced by the trigger and offline selection criteria. A detailed Monte Carlo simulation of the trigger, including the effects of the variations with time of the beam axis position with respect to the detector and of trigger algorithms, has been used to derive the efficiency as a function of proper time for each of the decay modes analyzed. This method has been validated measuring B^+ and B_d^0 lifetime in $D\pi$ modes collected by the same trigger used for the mixing analysis. The results ($\tau(B^+)(ps) = 1.661 \pm 0.025 \pm 0.013$, $\tau(B_d^0)(ps) = 1.511 \pm 0.023 \pm 0.013$, $\tau(B_s^0)(ps) = 1.598 \pm 0.097 \pm 0.017$) are consistent with world averages. The systematics are at the level of 1% and demonstrate that the the trigger bias is well under control. A similar analysis is currently under way using the same semileptonic B_s^0 sample used here. When completed, it will give the best measurement of B_s^0 lifetime in a flavor specific decay. For the time being a result consistent with the world average with a statistical uncertainty of 2% has been reported by CDF.

6. Flavor Tagging

Identifying the initial flavor of the B mesons at hadron colliders has always been a critical task due to the busy environment of b events in $p\bar{p}$ collisions. To determine the B_s^0 flavor algorithms have been developed relying either on the other b -hadron in the event, Opposite Side (OS) taggers, or on the expected charge correlation ($B_s^0 - K^+$) between the B_s^0 flavor and the kaons emerging close to the B_s^0 flight direction from the fragmentation and hadronization process, Same Side

Kaon (SSK) tagger. Five different OS taggers are used here:

- A Soft Muon Tagger (SMT), based on the detection of muons, with $P_T > 1.5$ GeV/c and pseudorapidity $|\eta| < 1.5$ from $b \rightarrow \mu^- X$ decays. The dilution is parameterized as a function of a muon likelihood and muon momentum relative to the jet axis, P_T^{rel} , to account for the higher dilution expected at higher P_T^{rel} due to lower $b \rightarrow c \rightarrow l^+$ sequential background.
- A similar algorithm, Soft Electron Tagger (SET), uses b decays to electrons with $P_T > 2.0$ GeV/c detected in the central electromagnetic calorimeter.
- Three different Jet Charge Taggers, where a weighted sum of track charges in opposite side jets is correlated with the initial b -quark charge sign. The three algorithms differ on the choice of the tagging jet: jet containing an identified secondary vertex (JVX), jet characterized by at least one displaced track (JJP) or the highest P_T jet in the event (JPT).

All the taggers have been tuned on an inclusive and almost pure sample of $\approx 10^6$ semileptonic b decays from the lepton + SVT trigger. The dilution of each different algorithm is determined, as a function of several variables, from the the trigger lepton charge after correction for mixing and $b \rightarrow c \rightarrow l^+$ background. Taggers are ranked in order of their expected dilutions and only the decision from the highest dilution tagger available in any single event is used.

Since the calibration sample for the dilution may be different in certain aspects (e.g. P_T spectra) from the signal sample a scale factor (S_D) is allowed for each of the 5 tagging algorithms. The S_D factors for the semileptonic and hadronic analysis are fixed by measuring the B_d^0 oscillation frequency and its amplitude using respectively the high statistics $B_{d,u} \rightarrow l D \nu X$ and $B_{d,u} \rightarrow J/\psi K^{(*)}/B_{d,u} \rightarrow D^{(*)} \pi$ samples. A summary of the tagging figure of merit εD^2 is reported in Tab. 2. The scale factors are consistent with 1 within the precision allowed by the present statistics.

7. Results and Perspectives

Following [3] an amplitude scan is performed, where, at each value of the mixing frequency, an amplitude A is fitted from the data. The amplitude A should be consistent with 0 for mixing frequencies far from the true value of Δm_s and with 1 in its vicinity. This method allows for a straightforward way to combine several measurement (semileptonic and hadronic) as well as results from different experiments.

We determined systematic uncertainties on the amplitude A using large toy MC experiments to minimize the effect of the limited statistics. The biggest effects on systematic uncertainties at high value of Δm_s come from the level and the dilution parameterization of the prompt background for the semileptonic analysis (contributing $\sigma_A \simeq 0.15$ @ $\Delta m_s = 20 \text{ ps}^{-1}$) and the dilution scale factor for the hadronic analysis ($\sigma_A \simeq 0.3$ @ $\Delta m_s = 20 \text{ ps}^{-1}$). It should be noticed that the latter will certainly be reduced with more data since it is limited by the available number of $B_{d,u}$ hadronic decays. In any case the combined systematic uncertainties are much smaller than the statistical uncertainties on the present measurements, for any value of the mixing frequency.

The present CDF sensitivity is dominated by the semileptonic result: $\Delta m_s > 7.7 \text{ ps}^{-1}$ @ 95% C.L. with a sensitivity of 7.4 ps^{-1} . The combined semileptonic and hadronic analysis limit is $\Delta m_s > 7.9 \text{ ps}^{-1}$ @ 95% C.L. while the combined sensitivity increases to 8.4 ps^{-1} .

Combining the CDF measurement with previ-

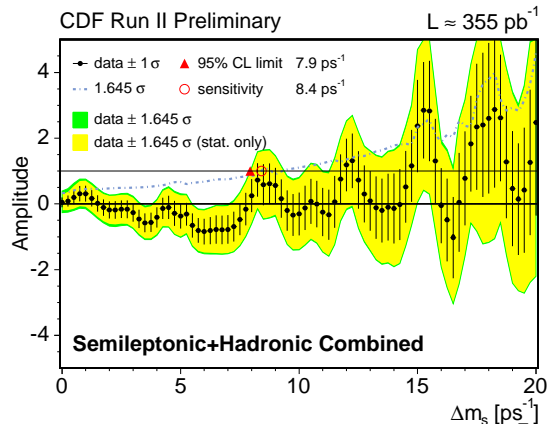


Figure 3. Amplitude scan for the combined $B_s^0 \rightarrow D_s^+ l^- X$ and $B_s^0 \rightarrow D_s^+ \pi^-$ analysis.

ously available results does not change the actual limit and only marginally improves the sensitivity (from 18.2 to 18.6). It can be noticed, however, that the current sensitivity of CDF II data is relatively better behaved at higher Δm_s than most of previous experiments due to the valuable hadronic sample that will dominate the sensitivity in future higher statistics searches for B_s^0 oscillations.

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